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Ecosystem-based design rules for marine sand extraction sites

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ABSTRACT

The demand for marine sand in the Netherlands as well as globally is increasing. Over the last decades, only shallow sand extraction of 2 m below the seabed was allowed on the Dutch Continental Shelf (DCS). To guarantee sufficient supply and to decrease the surface area of direct impact, the Dutch authorities started to promote sand extraction depths over 2 m for sand volumes over 10 million m^3. The ecological effects of deep sand extraction, however, are still largely unknown. Therefore, we investigated short-term effects (0–2.5 y) of deep sand extraction (20–24 m) and compared these with other case studies such as, regular shallow sand extraction on the DCS (2 m) and an 8 m deepened shipping lane. For intercomparison between case studies we used tide-averaged bed shear stress as a generic proxy for environmental and related ecological effects. Bed shear stress can be estimated with a two-dimensional quadratic friction law and showed a decrease from 0.50 to 0.04 N m^{-2} in a borrow pit in 20 m deep water and extraction depths up to 24 m. Macrozoobenthos in a borrow pit with a tide-averaged bed shear stress of around 0.41 N m^{-2} is expected to return back to pre-extraction conditions within 4–6 year. When tide-averaged bed shear stress decreases below 0.17 N m^{-2} enhanced macrozoobenthic species richness and biomass can occur. Below a tide-averaged bed shear stress of 0.08 N m^{-2}, increasing abundance and biomass of brittle stars, white furrow shell (*Abra alba*) and plaice (*platessa platessa*) can be expected. Below 0.04 N m^{-2}, an overdominance and high biomass of brittle stars can be expected whereas demersal fish biomass and species composition may return to reference conditions. Next to changes in faunal composition, a high sedimentation rate can be expected.

Ecological data and bed shear stress values were transformed into ecosystem-based design (EBD) rules. At higher flow velocities and larger water depths, larger extraction depths can be applied to achieve desired tide-averaged bed shear stresses for related ecological effects. The EBD rules can be used in the early-design phases of future borrow pits in order to simultaneously maximise sand yields and decrease the surface area of direct impact. The EBD rules and ecological landscaping can also help in implementing the European Union's Marine Strategy Framework Directive (MSFD) guidelines and moving to or maintaining Good Environmental Status (GES).

1. Introduction

Coastal zones are marked by many human activities such as fishing, shipping, wind farming, dredging, disposal of dredged sediment, beach nourishment, sand extraction, and the extraction and transport of oil and gas. These activities have different impacts on the marine environment and most of them are likely to intensify in the future (Jongbloed et al., 2014). Marine sand extraction in the Netherlands as well as globally is also intensifying (Stolk and Dijkshoorn, 2009; ICES, 2014a). In the Netherlands, 24 million m^3 of marine sand is used annually with 12.5 million m^3 for coastal nourishments and 9 million m^3 for construction (ICES, 2014a). An increase up to 85 million m^3 is anticipated to counteract effects of sea level rise (Deltacommissie, 2008). Considerable

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volumes are extracted in surrounding countries, in the UK 16.8 million m^3, in France 12 million m^3 and in Denmark 10.5 million m^3 per year. In Belgium, each year almost 4 million m^3 sand is extracted and 2.5 million m^3 is imported from the Netherlands (ICES, 2014a).

Over the last decades, sand extraction depths were limited to 2 m under the seabed on the Dutch continental shelf (DCS). The potential of sand extraction with depths over 2 m was first explored in 1999 during the PUTMOR study, in a deep borrow pit in front of the Port of Rotterdam (PoR) with sand extraction depths between 5 and 12 m (Boers, 2005). The PUTMOR study concluded that there were no indications that deep sand extraction would lead to unacceptable effects and that recovery of benthic assemblages would be possible (Boers, 2005). Deep sand extraction was therefore considered to be a promising alternative for sand extraction projects over 10 million m^3 sand. For the construction of Maasvlakte 2 (MV2), a 20 km^2 seaward expansion of the PoR, the Dutch authorities permitted sand extraction deeper than the regular 2 m, primarily to decrease the surface area of direct impact. Between 2009 and 2013, approximately 220 million m^3 sand was extracted from the MV2 borrow pit with an average extraction depth of 20 m under the seabed. To guarantee sufficient supply of marine sand in the intensively used coastal zone, the Dutch authorities now allow deep sand extraction for sand extraction volumes over 10 million m^3 (IDON, 2014).

Although deep sand extraction clearly limits the surface area of direct impact, effects of deep borrow pits on marine life on the DCS are still largely unknown. Our objective is to compare effects of extraction depth on macrozoobenthos and demersal fish and to recommend on optimised extraction depths for future borrow pits. We compared ecological effects for three case studies: regular shallow sand extraction (2 m), a deepened shipping lane (8 m) and deep sand extraction (20–24 m) in a large borrow pit.

Macrozoobenthos in the southern North Sea correlates with sediment parameters (Heip et al., 1992; Künitzer et al., 1992; Holtmann et al., 1996; Degraer et al., 1999; Van Hoey et al., 2004, 2007; Degraer et al., 2008; Verfaillie et al., 2009). Next to sediment parameters, salinity (Callaway et al., 2002; Reiss et al., 2010, 2011) and bed shear stress (Herman et al., 2001; Ysebaert et al., 2003; de Jong et al., 2015a) also influence macrozoobenthos.

Bed shear stress the amount of force per unit of seabed surface area exerted by flowing water and plays a role in sediment transport processes, the formation of bedforms, and sedimentation or erosion of the seabed. Bed shear stress is also influencing grain size, mud and organic matter content of the sediment. In the North Sea coastal zone, grain size is positively correlated with bed shear stress (spearman rank correlation: around +0.4) (de Jong et al., 2015a). On the crests of sand waves, shear stress values are generally higher (~0.6 $N\,m^{-2}$) and the sediment is coarser (~300 μm), whereas in troughs, shear stress is lower (0.44 $N\,m^{-2}$) and grain size is finer (~280 μm) (de Jong et al., 2015a). Due to sand extraction, larger differences in bed shear stress can be expected and correlations between sediment parameters and bed shear stress may become stronger. In the UK, suggested limits for acceptable changes in grain size after marine aggregate extraction were based on the natural range (Cooper, 2012). Sediment characteristics after deep sand extraction continue to change due to sedimentation of fine sediment until the borrow pit is filled (Thatje et al., 1999; Desprez, 2000; de Jong et al., 2015b).

For intercomparison between case studies, we used tide-averaged bed shear stress as a generic proxy for environmental and related ecological effects. Ecological data and bed shear stress values were combined and transformed into ecosystem-based design (EBD) rules. These rules can be used in the design of future borrow pits to maximise sand yields and simultaneously decrease the surface area of direct impact for different ecological scenarios.

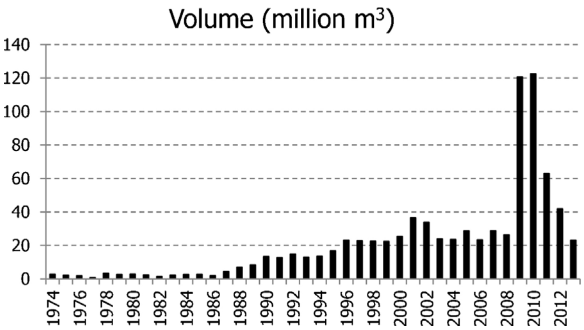

Fig. 1. Total volume of extracted marine sand in million m^3 per year on the DCS. The peak in 2009–2012 is due to the large-scale and deep sand extraction for MV2. *Source:* Rijkswaterstaat (ICES, 2014a).

We aim to answer the following questions:

(i) What are the ecological effects of the different sand extraction depths on the Dutch Continental Shelf (DCS)?
(ii) What are the optimised extraction depths to achieve desired bed shear stresses and related ecological effects for different pre-extraction water depths and flow velocities?
(iii) What role can ecosystem based design rules based on bed shear stress play in the design of future borrow pits outside the DCS?

2. Description of different cases of sand extraction depths on the Dutch continental shelf

We describe the following case studies on the Dutch Continental Shelf (DCS): regular shallow sand extraction, the 8 m deepened "Euromaasgeul" shipping lane and the deep and large-scale Maasvlakte 2 (MV2) borrow pit.

2.1. Shallow sand extraction

Before 1987 less than 5 million m^3 of marine sand was extracted annually from the Dutch Continental Shelf (DCS) and increased to nearly 20 million m^3 in 1995 (Fig. 1). From 1996 onwards, over 24 million m^3 of marine sand was extracted yearly for coastal nourishments and construction purposes (Stolk and Dijkshoorn, 2009; ICES, 2014a). Generally, only shallow sand extraction of 2 m below the seabed is allowed and only in the area between the continuous 20 m isobath and the 12 nautical mile boundary (Fig. 2) (IDON, 2005, 2014). Between 2006 and 2014 the surface area impacted by sand extraction increased from 7.5 to 45 km^2 (ICES, 2014a).

2.2. Shipping lane

North of the MV2 borrow pit (Fig. 2, no.1), a 57 km long and 23 m deep shipping lane "the Euromaasgeul" is situated which was realised in the 1970s to guarantee access to the Port of Rotterdam (PoR). Fine dredged material from the entrance of the shipping lane is dumped at the deepened disposal site "Verdiepte Loswal" (Fig. 2, no. 3) and the coarse fraction at disposal site North "Loswal Noord" near the entrance of the PoR. In the specific sampling area within the shipping lane, 8 m sand was extracted.

2.3. Maasvlakte 2 (MV2) borrow pit

For the harbour extension Maasvlakte 2 (MV2), approximately 220 million m^3 of sand was extracted between 2009 and 2013 (Fig. 1) from the MV2 borrow pit with an average extraction depth of 20 m under the seabed (Fig. 2, no. 1). This reduced the surface area of the borrow pit from 110 km^2 at 2 m extraction depth to only